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Citation for published version:
Cloude, SR, Woodhouse, I, Hope, J, Minguez, JCS, Osborne, P, Wright, G & Wilson, A (ed.) 2002, The Glen Affric Project: forrest mapping using dual baseline polarimetric radar interferometry. in A Wilson & S Quegan (eds), *Proceedings of the Third International Symposium on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications.* vol. 475, pp. 333-338.
<http://adsabs.harvard.edu/abs/2002ESASP.475..333C>

Published In:
Proceedings of the Third International Symposium on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications

THE GLEN AFFRIC PROJECT : FOREST MAPPING USING DUAL BASELINE POLARIMETRIC RADAR INTERFEROMETRY

S. R. Cloude[1], I.H. Woodhouse[2], J. Hope[3], J.C. Suarez Minguez[3], P. Osborne[4], G.[1] Wright[5]
[1]AEL Consultants, Cupar, Fife, KY15 5AA, Scotland, e-mail : scloude@aelc.demon.co.uk
[2]The University of Edinburgh, Dept. of Geography, Drummond St., Edinburgh, EH8 9XP, Scotland
[3]Forest Research, Midlothian, EH25 9SY, Scotland
[4]The University of Stirling, Dept. of Environmental Sciences, Stirling, FK9 41A, Scotland
[5]Macaulay Land use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland

Abstract— In this paper we introduce the Glen Affric radar project, a multi-disciplinary program addressing the potential of polarimetric radar interferometry to provide quantitative vegetation structural information of importance in forest mapping and ecology studies. We present for the first time a comparison of results from L-band repeat pass SAR imagery with detailed in-situ measurements of forest height for the test site.

I. INTRODUCTION

The conservation and management of remaining natural and semi-natural habitats of the countryside is now of greater importance than ever before, due to continuing pollution, physical destruction and fragmentation, which may lead to increasing rates of species extinction, loss of diversity and general deterioration in habitat quality [1]. A fundamental requirement for management is widespread and frequent monitoring, which can only be done effectively using some form of remote sensing.

The key approach taken in this project is to investigate the use of fully coherent polarimetric SAR data in this important role. SAR is sensitive to structural parameters of vegetation and, in particular, L-band polarimetric SAR is especially suited to vegetation mapping because it is sufficiently sensitive to both canopy and sub-canopy parameters. By utilising the capability of repeat pass interferometry we have the potential to produce a true ground DEM of the test site (without vegetation bias), estimate forest height and canopy extinction [2,3]. The use of repeat pass fully polarimetric interferometry is fundamental for the following reasons:

- The influence of surface topography can be accounted for in the polarimetric analysis without the requirement for external reference DEMs
- Tree canopy height and density can be directly inferred from the data
- The Polarimetric response from the canopy can then be considered separately of the signal from the forest floor, leading to improved estimates of surface conditions such as roughness and moisture content.

These results are expected to allow both general species discrimination and determination of structural biophysical parameters, giving a more complete description of the vegetation than is possible using current remote sensing approaches.

II. THE GLEN AFFRIC TEST SITE

In Scotland, the natural regeneration of the Caledonian forest (consisting principally of Scots pine, *Pinus sylvestris*) over wide areas is seen as a major objective for Scottish conservation managers. Native pinewoods are specified in the EU Directive on the Conservation of Natural and Semi-natural Habitats and of Wild Fauna and Flora (92/43/EEC) (generally referred to as the "EU Habitats Directive") and are a key habitat specified in the UK Biodiversity Action Plan [4]. Effective monitoring is required if the impact of specific active strategies, as well as other environmental change factors, is to be measured and understood. Furthermore, European legislation now requires national conservation agencies, such as Scottish Natural Heritage, to monitor change and report on the status of nationally and internationally important conservation areas.

The routine application of optical remote sensing to conservation management of semi-natural vegetation areas in the UK has been limited due in part to the inability of available data to provide meaningful quantitative information needed for ecological interpretation as a result of coarse spectral and spatial resolutions. The problem of spectral inseparability may be addressed by analysing data of high spectral resolution and such data are becoming recognised as a tool in ecological investigations [5,6]. However, work is required to determine the appropriate scale of observation for particular ecological applications so that new technologies can be successfully applied to ecological studies.

Proc. 3rd International Symposium, 'Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications', Sheffield, UK, 11-14 September 2001 (ESA SP-475, January 2002)

In order to address these issues, a BNSC-NERC sponsored radar measurement campaign was held in the UK in May/June 2000. Glen Affric was one of the selected sites and 6 radar passes were gathered with offset baselines of 10 and 20m enabling single and dual baseline interferometric analyses. In this paper we summarise the objectives and show results from the data analysis and comparison with ground truth.

Test Site Location and Topography

The test area is located in the North West Highlands of Scotland as shown in figure 1. The area is mountainous and combines several important challenges for radar remote sensing, including heterogeneous forest cover, sloped terrain and a broad distribution of tree heights.

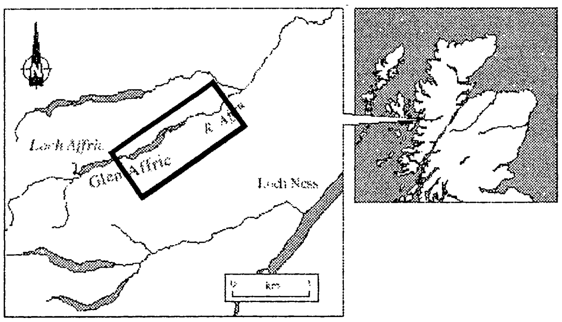

Figure 1 : Location of Glen Affric Test Site

Despite its relative isolation, the site has been extensively studied using conventional aerial photography combined with comprehensive ground surveys and hence provides a good site for quantitative validation studies [8,9,10].

To illustrate the nature of the terrain slopes in the region we show in figure 2 a radar-derived unwrapped phase image of a portion of the south side of the loch. This phase image was obtained from the 10m baseline data using the coherence maximiser [2] to reduce as far as possible the phase noise. The main forested test regions lie along the loch side and we can clearly see the varied topography of the site.

Figure 3 shows a photograph of our forest test stand in the scene. We note the mixed species and heterogeneity of the tree cover. Tree heights vary from a few meters up to 30m or more for the large Scots Pines.

III. FOREST SCATTERING MODEL

To interpret the coherence information for the test site we need to employ a multi-layer coherent model of forest scattering.

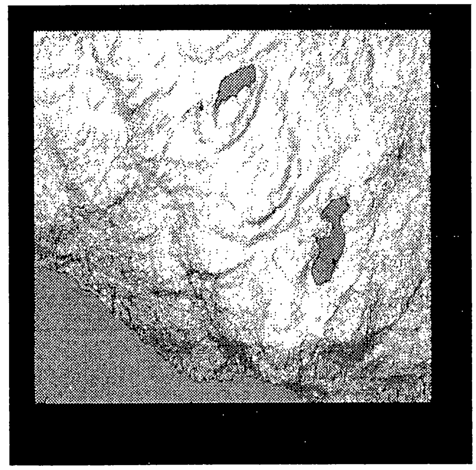

Figure 2 : Relative Height Map Obtained From 10m Baseline Repeat Pass Radar Interferometry

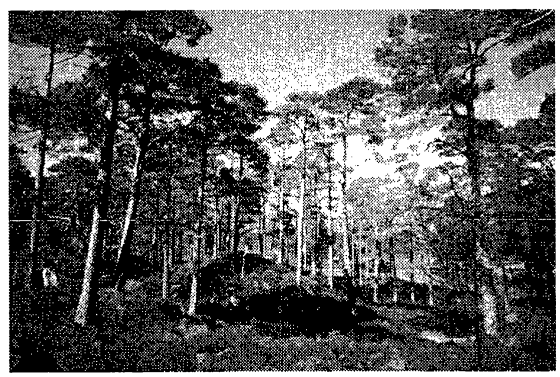

Figure 3 : Forest Test Stand in Glen Affric

According to the 2-layer model derived in [2,3,11], the complex interferometric coherence for a random volume over a ground can be written as a function of polarisation scattering mechanism $\underline{w}$ as

$$\tilde{\gamma}(\underline{w}) = e^{i\phi}\frac{I_2 + m(\underline{w})}{I_1 + m(\underline{w})} \qquad \text{- 1)}$$

where only m is a function of polarisation and I_1 and I_2 are volume integrals as shown in equation 2.

$$\begin{aligned} I_1 &= \frac{1}{p_1}(e^{p_1 h_v} - 1) \\ I_2 &= \frac{1}{p_2}(e^{p_2 h_v} - 1) \end{aligned} \qquad \text{- 2)}$$

The complex propagation constants p_1 and p_2 are defined as

$$p_1 = \frac{2\sigma}{\cos\theta_o}$$
$$p_2 = \frac{2\sigma}{\cos\theta_o} + i\frac{4\pi B_n}{\lambda R \sin\theta_o} \quad \text{- 3)}$$

where B_n is the normal component of the baseline of the interferometer. We see that we have 4 unknown parameters, namely

m – the ground to volume scattering amplitude
σ – the mean volume extinction
h_v – the height of the forest
ϕ - the ground topographic phase

However we have only two measurements (the amplitude and phase of the coherence). Hence a single channel interferometer is not able to provide unambiguous structural information. We see that by adding a second polarimetric channel we will add two new measurements while adding only one new unknown (m) and hence obtain a deficit through 4 measurements to 5 unknowns. Similarly, by adding a third channel we obtain 6 measurements for 6 unknowns. Hence by employing full polarimetric interferometry we can invert equation 1 to obtain quantitative parameter estimates.

The inversion is implemented in 3 stages:

Stage 1 : Least Squares Line Fit

The first stage is to find the best-fit straight line inside the unit circle of interferometric coherence. To do this we vary two phase variable ϕ_1 and ϕ_2 as shown in figure 4. Each pair defines a line and we choose the pair that minimises the MSE between the line and set of coherence points. We use 9 points for each line fit, obtained from interferograms in the following polarisation channels

opt1,opt2,opt3,HH-VV,HH+VV,HH,VV,HV,LL

where 'opt' are the optimum coherence states obtained using the algorithm in [2]. The state LL is left circular polarisation at either end of the baseline.

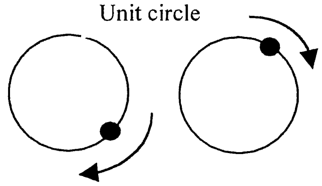

Figure 4 : Phase based least square line fit

Stage 2 : Vegetation Bias Removal

In the second stage we must choose one of the pair ϕ_1,ϕ_2 as the underlying ground topographic phase. This we do by selecting the point with the highest count of polarisation channels lying between the candidate ground point and the HV phase. This provides a quick method for selecting the ground point ϕ.

Stage 3 : Height and Extinction estimation

To estimate the two remaining parameters we use the line and estimate of ϕ together with equation 2 to find the intersection point between the line and the curve corresponding to equation 2.

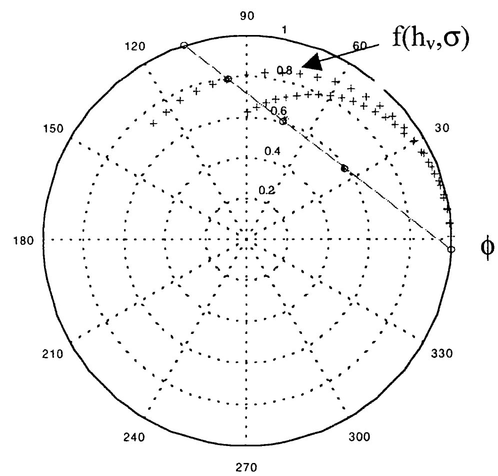

Figure 5 : Height and Extinction estimates, non-physical solution (lower curve), correct solution (upper curve)

Figure 5 shows two such intersections, one of which crosses the line to bisect coherence values. This cannot be a physical solution, as it generates negative ground contributions. We take as the true solution the parameters which cause the curve to intersect the line at the coherence value furthest from ϕ (upper curve in figure 5). This ensures non-negative ground scattering components and makes the weak assumption that in at least one of the 9 polarisation channels we observe a very small ground-to-volume scattering ratio. This can be reasonably assumed in the HV channel as well as in at least one of the optimum coherence channels.

Note that the model assumes a uniform density of scatterers from ground to crown. However, on inspection of figure 3, we can see that this is not typical of the Scots pine tree structure. Previous validations of this algorithm have been carried out, but only on dense pine trees with more uniform vertical density profiles [11] Hence this site represents an interesting new test for the technique. Analysis of the model indicates that the effect of such high canopies will be to overestimate the extinction and the tree height. Dual baseline techniques are expected to resolve this canopy structure problem but here we are interested in the errors caused in single baseline inversions by such structural features.

In anticipation of this problem, we have modified the model of equation 1 as follows

- We assume that σ is known from a prior modelling or other means. Here we set it to a value of 0.1 dB/m for L-band, although for shallow canopies the value chosen does not strongly influence the results.
- We introduce a new free parameter into the integral I_2, namely the phase elevation of the canopy as shown in equation 4.

$$I_2 = \frac{1}{p_2}(e^{p_2 h_v} - 1)e^{i\phi_{can}} \qquad -4)$$

We can now estimate the canopy depth, ground topography and tree height using the inversion scheme.

IV. RADAR DATA ANALYSIS

To demonstrate the basic quality of the radar data, we show in figure 6 composite images of the three optimum channels (opt1,opt2 and opt3) for the 10m (lower) and 20m (upper) baselines.

The forested regions are clearly shown as dark areas with low coherence. Note how the longer baseline is more sensitive to the smaller vegetation cover. Here we concentrate only on the shorter 10m baseline.

This coherence data was combined with the other 6 channels and used as input into our model based parameter estimation technique to estimate the local forest height. Figure 7 shows a map of vegetation height obtained from this algorithm.

V : TREE HEIGHT VALIDATION STUDIES

The next stage of our studies was to validate the heights obtained in the map shown in figure 7. To do this concentrated effort on a mixed stand close to the southern shore of the Loch.

Ground Truth Measurements

Since the test site was heterogeneous and rather sparse, with ground variations of 20m, simple stand averaging of tree heights was inappropriate. Detailed survey transects were therefore taken over two test sites, taking measurements of x, y and z of the tree base (and occasional spot heights), species, diameter at breast height (dbh) and tree height.

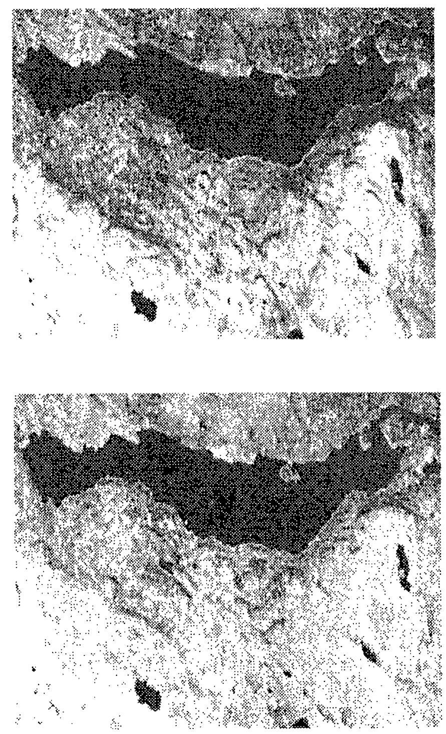

Figure 6: RGB Optimum Interferometric Coherence Images for 10m (lower) and 20m (upper) baselines

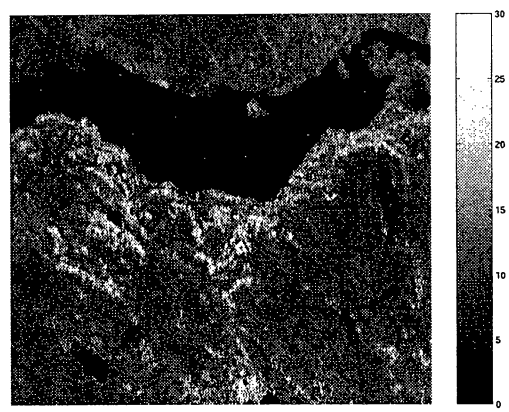

Figure 7 : Vegetation Height Map Obtained from 10m Baseline Data

When possible the height of start of crown and crown width were also measured. The height to crown was measured to the lowest live first-order branch. All measurements were related to a single "reference point" that was located using a GPS. Two main transects were made – one in approximately the SAR range direction, the other perpendicular to this.

The relative accuracy of the tree measurements are less than 1m (x, y, z) for the ground locations and approximately +/- 2m for height for the largest trees. As can be seen from figure 3, a major source of error is simply deciding what constitutes the top of the tree. In addition, the fact that not all the larger trees were vertical meant that the x,y locational uncertainty for the crown is also a further +/- 2m.

The absolute location errors are dependent upon (a) the 3-D accuracy of the GPS location of the reference point, and (b) the orientation of the "reference direction". The second of these is the most problematic, as with no visible landmarks a simple compass bearing was used as an indication of orientation. To compensate for this, 3-D measurements were also made along the centre of an access track to allow final adjustments to the absolute locations. The tree locations and spot heights (points) are shown in figure 8, as well as the expected crown locations.

The E-SAR flight geometry was used to determine the range and azimuth locations of the tree bases and spot heights, as well as the tree crowns. Two corner reflectors located at either end of the complete data take were used to help correlate the image co-ordinates to map co-ordinates. All calculations were carried out in the UK Ordnance Survey projection with altitudes above mean sea level. We estimate final locational uncertainties (for ground points) between field data and SAR data to be in the region of +/- 3m in azimuth and +/- 5m in range (approx. 4 pixels). Crown locations are more uncertain and are considered below.

Representation of Ground Data

The detailed test site consisted primarily of Scots Pine, with a few birch (<5% of total number and all less than 10m tall). For visualising the data, pines with a dbh less that 30cm are given as conical crowns, otherwise they are represented by a hemi-spheroidal shape model using information on crown height and width. It should be noted that this crown shape represents the outermost elements of the branch structure, rather than an actual well-defined crown (which as can be seen from Figure 3 is never well defined for the taller pines).

For about 20% of the trees the crown width or height were not measurable but for visual purposes the following relationships are used: crown width = one third of the tree height, and height to crown = one half of the tree height.

Comparison Between Retrieved and Measured Tree Heights

Figure 9 shows the range and azimuth transects respectively and clearly demonstrate that the retrieved height pattern is well correlated with the measured trees.

Underlying topography is not shown in these images. Trees that lie within 5m off the transect line are included in the comparison and are located in the figure by their true horizontal distance along the transect. The starred points and connecting line represent the retrieved height value for the crown **slant range** location in the retrieved data (i.e. spot heights will be unchanged, but trees of a given height are compared against the retrieved values corresponding to their slant range ("lay-over") location). In order to help account for locational errors, the retrieved height shown is actually a 3x3 pixel average centred on the slant range location.

This way of comparing the data is required to account for the expected response from individual trees. In such cases the retrieved height will be located not at the base of the tree, but rather at the slant range location of the crown. This approach to the retrieval procedure introduces another locational uncertainty since the height of the scattering centre (and hence slant range) will not be the same as the measured tree height. Such uncertainties may help explain the results of the range transect in Figure 9 whereby some of the taller trees do not always seem to be well correlated in range location to the higher retrieved values. Despite this, the correlation between measured and retrieved heights in the range transect give a linear Pearson's correlation co-oefficient R=0.88. For the azimuth transect the results also appear well correlated with R=0.90.

Discussion of Results

Despite the reasonable correlation, there are three noticeable discrepancies between the radar results and ground truth. The first is that the retrieval process generally appears to underestimate the tree heights. This is fully expected, as the L band response is sensitive to combined ground and canopy features in all polarisation channels.

The second is that where the field measurements imply no trees, the retrieval can indicate positive tree heights of about 5m and up to as much as 10m. This is caused by SNR coherence problems in non-vegetated areas yielding spurious phase shifts in the data. Masking based on the HH/VV polarimetric coherence should help identify such areas.

A third problem is that in some instances the retrieval *significantly* underestimates the tree height. For example, in the range transect, at around 20m, there is a sharp change between small pines and taller ones behind. The retrieval process does not identify the taller trees until nearer 25m. It is quite possible that what is happening here is that the slant range distances for the shorter canopy at 15m coincide with the slant range to the taller crowns at 20-25m. With canopy scattering from two distinct locations and no clear ground response, it is possible that in this case the current method fails to determine a realistic tree height. It is problems of this nature will be the focus of future studies, which include a forthcoming NERC funded research project.

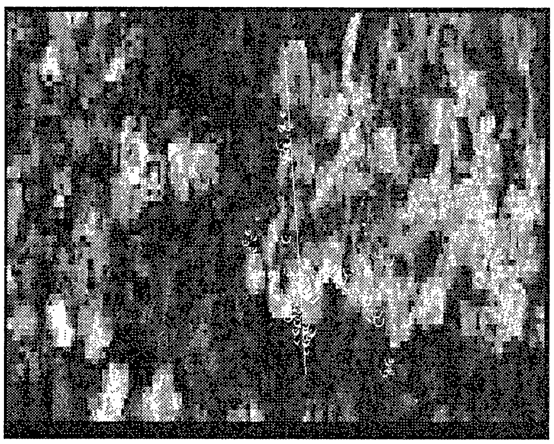

Figure 8: Location of Ground Truth Measurement Points superimposed on Radar Derived Tree Height Map

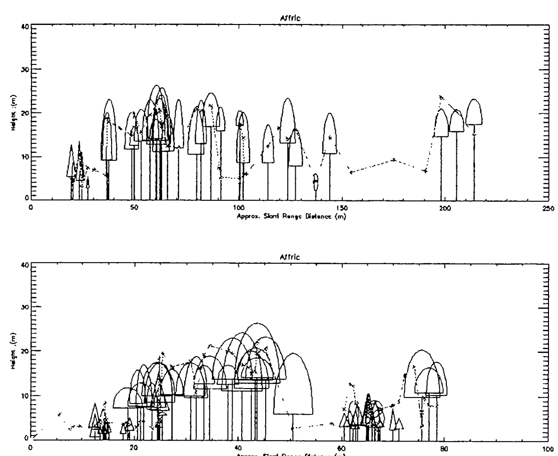

Figure 9 : Tree height Estimates vs. ground truth for the two transects: azimuth (upper) and range (lower)

V1. CONCLUSIONS

In this paper we have introduced the Glen Affric radar project and described the test site and its importance as a validation site for an assessment of polarimetric radar interferometry. We have shown, through ground truth validation that the radar data is capable of providing important quantitative structural forest information. Future studies will concentrate on further comparisons of the radar observations with ground truth, especially for underlying ground topography and canopy structure.

VII ACKNOWLEDGMENTS

The data provided for the Glen Affric project was collected under the UK NERC/BNSC sponsored SHAC campaign.

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